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EXECUTIVE SUMMARY:

Over this past quarter we have completed the pilot study with BF Goodrich. We are continuing to work on Visualization research and on developing the assembly modeler program.

This status report is divided into the following six subsections:

VISUALIZATION RESEARCH:

We are continuing to study and implement visualizations of assembly sequences in the dual graph representation. Achievements and goals fit in three categories often studied when visualizing large, complex, and abstract structures. These categories are: 1) Representation of single assembly sequences; 2) Layout of all assembly sequences in the visualization space; 3) Navigation in the visualization space.

Representation of single assembly sequences:

In the previous liaison diagram and its dual graph drawing, single assembly sequences could be selected by picking an assembly node in the dual graph and the corresponding path in the liaison diagram (top to bottom) would be highlighted. The visualization of the selected sequence was provided through detail drawings of each assembly state in the liaison diagram.

Other visualization techniques, however, can be used. There are two common representations in the visualization of a single assembly sequence: the static exploded view and the dynamic animated view. In the static exploded view, each assembly sequence is represented in three dimensions and shows both direction (+x, -x, +y, -y, +z, and -z) and order (distance from the center) for the sequence. In the dynamic animated view, the direction and order of the sequence is illustrated temporally instead of spatially.

In the current system, an assembly sequence visualization is shown by selecting an assembly node in the dual graph. Development includes an automatic exploded view when the navigation feature is complete. Furthermore, visualization development for a single assembly sequence aims at helping the users define or design their own representations.

Layout of all assembly sequences in the visualization space:

Proximity of assembly nodes in the dual space should be defined by some similarity between the nodes. We are approximating similarity measures by placing a link between two sequences when they can be derived from each other via one swap of two consecutive states in the sequences. For example, if two sequences M and N have these forms:

$$M = (s0,s1,\ldots\ldots,si,sj,\ldots\ldots sN), \text{ and}$$
$$N = (s0,s1,\ldots\ldots,sj,si,\ldots\ldots sN).$$

A link or edge is placed between node M and node N.

Once links are established, the optimization algorithm for three dimensional graph drawings can be applied so that similar sequences are clustered and comparison task between sequences can be performed.

With the current system (which includes node linking and node placement optimization) we observe geometric patterns in the dual space for all sequences passing through the same assembly state. Future study includes other definitions of a link between two nodes -- hence two assembly sequences -- and other node placement algorithms.

Navigation in the visualization space:

One of the most important components in interactive visualization is navigation ability. The user can navigate through a complex structure and can move around and compare all assembly sequences to find the best one.

The detail level for each assembly sequence (while navigating through visualization space) is defined by a degree of interest (DOI) function often used in the visualization of complex, abstract structures. DOI is a function of both ***semantic distance*** (SD) and ***a-priori importance*** (API). For instance, SD can be the distance from the viewpoint, and API is parameterized by factors of assembly sequence optimality. The visualization of assembly sequences is mapped through DOI into different graphical attributes such as colors, size, and icons.

PROTOCOL ANALYSIS:

The purpose of protocol analysis is investigating knowledge models and decision making strategies used by design engineers in assembly planning. Three main issues need study based on protocol analysis: 1) the relative importance of assembly constraints in decision making; 2) the process or stages of decision making; 3) the use of assembly constraints in different planning stages. Protocol analysis results will help define functional and user interface requirements for the assembly planner we are developing. The protocol analysis has two phases: the pilot study and the experiment.

Pilot study:

The pilot study is complete. Three design engineers from BF Goodrich participated the pilot study. Subjects were first asked to fill out biographical questionnaires. Then the experimenter explained the procedure and instructed subjects to think aloud. When subjects were ready, they were given part drawings from an aircraft's wheel brake. The drawings were randomly ordered to avoid influencing the subject's decision making process. The subject was to develop an assembly sequence for the brake (has about thirty components). Subjects were given a scratch-pad for ideas and a separate sheet of paper for the final assembly sequence. To track the subject's thought process, the subject was not permitted to erase anything. Subjects were to think aloud throughout the entire experiment: this is how verbal protocols were collected. During data collection, a peer (also a design engineer at BF Goodrich) sat with the subject and prompted the subject to think aloud when necessary. A cam-corder recorded the subject during the assembly planning task. The subject's verbal protocols were transcribed from the videotape and frequency data was collected and analyzed.

To examine the relative importance of assembly constraints, the experimenter can count all phrases, prepositions, words, or sentences related to using constraints to make decisions about assembly planning. For example, a segment of a subject's protocols is below:

> "I will assemble the torque plate first. It is a good base point because everything else builds up from the bottom, and it is the bottom-most point. I also saw them assemble it that way in the plant previously."

The first sentence in this segment indicates a decision the subject made for assembly planning. To make this decision, he used an assembly constraint that bottom parts should be assembled before top parts (as indicated by the second sentence in the segment). He further justified this decision by referring to past practices (as indicated by the third sentence). The frequency data and analysis can be used to develop a list of assembly rules or constraints for decision made by assembly planners. The list has a frequency associated with each rule or constraint and will show the relative importance of each.

Identifying thought processes:

To examine assembly planning processes, the experimenter identifies all phrases, prepositions, words, or sentences related to different aspects of assembly planning. For example, a segment of a subject's protocols is shown below:

"There are three main subassemblies: heat sink, piston housing, and torque plate.

I will assemble the torque plate first. It is a good base point because everything else builds up from the bottom, and it is the bottom-most point. I also saw them assemble it that way in the plant previously.

Finding parts needed to assemble torque plate.

I must decide which part to attach first to assemble torque plate. I will install shields first because they are inner most parts. I will be working from inside to outside for handling purposes. I will install rivets on shields. No, I must be able to handle torque plate. I will have interference problems. So I will just do the shields first....... Torque plate is ... assembled.......

I will set torque plate on table vertically so it is easy to stack carbon on it due to gravity. It all fits on top of each other in a stack. (Torque plate) can not stand up any other way because I can not put carbon on. This is the most efficient way.

First gather all heat sink materials together," etc....

From this segment of protocols, it becomes obvious that the assembly planning is divided into five main stages:

1. Identify main subassemblies (as indicated by the first part of the segment);

2. Select a subassembly to work on (as indicated by the second part of the segment);

3. Get the design information of parts involved in the subassembly (as indicated by the third part of the segment);

4. Sort out the sequence of parts for the subassembly (as indicated by the fourth part of the segment);

5. Orient the completed subassembly in the direction suitable for next subassembly (as indicated by the fifth part of the segment);

Stages 2 - 5 are repeated for each subassembly (the last part of the segment).

Each planning stage can be broken into substages. In this segment of protocols, we see many assembly rules or constraints used by the subject for assembly planning. Some assembly rules or constraints in this segment of protocols are: inner parts should be assembled before outside parts for easy handling; parts assembled earlier should not interfere with parts assembled later; and parts should be oriented to allow the installation by gravity.

To examine assembly rules or constraints in different assembly planning stages, the experimenter can count phrases, prepositions, words, or sentences that are related to rules or constraints in each stage. For example, the above protocol segments indicate two rules were used in stage 2, two in stage 4, and one in stage 5. We can also identify what particular assembly rules or constraints are used most in each stage of assembly planning.

Final protocol analysis results from the pilot study will be presented in the next quarterly report. We will also start the second protocol analysis phase in a couple of weeks (the actual experiment). Data collection and analysis of the experiment phase should be complete during February, 1994.

ASSEMBLY MODELER CONCEPTUAL DESIGN:

The number of feasible assembly sequences can managed by introducing constraints. A system that lets designers select constraints prior to automatic assembly sequence generation would reduce the number of feasible alternatives while giving designers the flexibility to look at several alternatives to the problem.

Establishing the criteria or rules assembly planners use to specify an assembly is critical. How criteria are specified, weighed, and measured must still be defined and how criteria affect automatic sequence generation must also be established. Once assembly criteria is determined, it is used not only as input to the assembly planner but also for visualization of sequences. For example, if an planner determines that three criteria must be met and are the most critical to the assembly, visualizations will be created to allow the engineer to compare assembly sequences based on their ability to meet the criteria.

We are developing an assembly modeler subsystem to let designers specify criteria and precedence relationships in advance. Considerations for this subsystem are:

1. ***Data Retrieval*** - would let designers retrieve information about previous designs, associated assembly sequences, and criteria for those sequences. Often, new products are based on old products and the assembly process need not be completely re-designed. *This function would include retrieving a current product.*
2. ***Criteria Selection*** - would allow the designer to specify important criteria for assemblies and help eliminate assembly sequences. It also could analyze previous designs (in terms of new criteria) to see if old sequences meet new criteria.
3. ***Specifying Precedence Relationships*** - would automatically generate precedence relationships based on product geometry. In some cases the designer may know certain relationships cannot be violated and he or she should have the ability to specify these relationships.
4. ***Specifying Sub-assemblies*** - would allow the designer to specify what parts constitute sub-assemblies before automatic generation. The number of required operations generating feasible sequences would be reduced.
5. ***Visual Representations*** - would provide designers with visualizations of products, assembly sequences, constraints, precedence relationships, etc.... The effectiveness of visualization depends on user's immediate needs given tasks performed.
6. ***Help*** - would aid designers interacting with the system.

Listed below are criteria identified as critical to assembly planning. To establish importance of these criteria, engineers at BF Goodrich will be asked to rate and rank the criteria after they have participated in our protocol analysis. Also, as described in the section *Protocol Analysis*, the type and frequency of constraints can be identified as the engineer talks through his thoughts during the protocol analysis.

Sequence Selection Criteria:

* Avoid collision of parts during assembly
* Avoid undue cost or time to assemble
* Avoid excessive reorientation
* Avoid unstable states during assembly (ex: assemble bolts that secure a part right after assembling that part)
* Avoid assembly moves that are difficult (ex-1: some assembly moves that are easy for people are very difficult to automate; ex-2: it is sometimes difficult to assemble 3 or 4 parts at the same time)
* Avoid assembly moves if there is a risk of part damage (ex: assembling a large part to a small delicate part)
* Avoid unsafe assembly moves (ex-1: in a process that uses both people and automated assembly, avoid sequences that require people to be around dangerous assembly equipment; ex-2: avoid an assembly stage that leaves wires or edges exposed that might injure people)
* Avoid sequences that require excessive fixtures, grippers, or tools (or that require expensive fixtures, grippers, or tools)
* Make sure that sequence allows proper access for assembly tools (ex: need access to hold nut while tightening a screw)
* Follow engineer's concept of good practice (ex-1: if filling a cup with oil, place cap on cup right away to avoid spilling or contaminating oil; ex-2: use the largest part as the base part)
* Design sequence so there are convenient stages for quality testing [ex: create functional subassemblies first and see if they work rather than assembling the entire product and then testing to see if it works. When the entire product is assembled, it may be difficult to see what is causing the problem and it may take more work to disassemble the product to fix it.]
* Engineers may need to follow a particular layout of equipment which may affect assembly sequence

Publications, Abstracts, Conferences:

Conference Submissions Accepted:

Automatic Generation of Assembly Plans: Human Factors Considerations: Submitted by Jennie J. Gallimore to the First Automation Technology and Human Performance Conference, Washington D.C., April 7-8, 1994

Human Factors Considerations in the Development of an Assembly Planning System: Submitted by Jennie J. Gallimore to the Specialized Symposium on Human Factors in Design for Manufacturing, Canada, August, 1994

Publications Submitted:

Gallimore, J. J., Gerace, J., and Mitta, D. Recognizing the Need for Human Factors in Advanced Manufacturing. Submitted to the Proceedings of the Industrial Engineering Research Conference (IERC). May 1994 in Atlanta, GA.

Abstract:

Traditional roles for human factors engineers in manufacturing fall within process and facilities engineering. Most human factors engineers work in job design, ergonomic workstation evaluation, facilities layout, and establishing consumer product requirements. Human factors engineers are rarely involved in developing new manufacturing technologies, tools or automated systems. Human factors roles should be expanded to include design of manufacturing technologies and processes that are used by engineering designers. This article addresses the need for human factors input, and provides an example of current research on assembly planning.

Other:

Dr. Gallimore participated in the Ergonomics in Manufacturing Workshop, November 18 and 19, 1993 sponsored by the National Science Foundation and the University of Cincinnati. The purpose of this workshop was to explore the role of human factors and ergonomics in manufacturing. The results will provide the NSF with input into future research directions.

Contact with Industry and Government:

We are continuing our work with B.F. Goodrich in Dayton, OH.

Goals for the Next Period:

1. Completion of data collection and analysis of the protocol experiment. An article based on the results will be submitted for publication.

2. We want to concentrate on algorithm development to integrate our research/develop a prototype within the next 3 months. We will begin by developing an assembly modeler and continue working on assembly generation algorithms.